
Four-Dimensional Imaging and Treatment Planning of Moving Targets

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Abstract

Four-dimensional CT acquisition is commercially available, and provides important information on the shape and trajectory of the tumor and normal tissues. The primary advantage of four-dimensional imaging over light breathing helical scans is the reduction of motion artifacts during scanning that can significantly alter tumor appearance. Segmentation, image registration, visualization are new challenges associated with four-dimensional data sets because of the overwhelming increase in the number of images. Four-dimensional dose calculations, while currently laborious, provide insights into dose perturbations due to organ motion. Imaging before treatment (image guidance) improves accuracy of radiation delivery, and recording transmission images can provide a means of verifying gated delivery.

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Precise knowledge and control of the three-dimensional dose distribution is considered to be essential for a favorable therapeutic outcome. The ability to deliver highly conformal dose distributions through intensity-modulated radiotherapy has become common for sites such as head and neck and prostate. When the target moves due to respiration, precise delivery of dose becomes more challenging and of concern. This is due in part to inadequate knowledge of the detailed dose delivered during motion [1, 2]. This article reviews three aspects of the irradiation of moving targets: (1) the imaging of moving objects, and understanding of such images; (2) the impact of respiratory motion on dose, and (3) a clinical example of image-guided/gated radiotherapy delivered to a moving target. For the interested reader, additional information on the irradiation of moving targets appeared in 2004 [3].

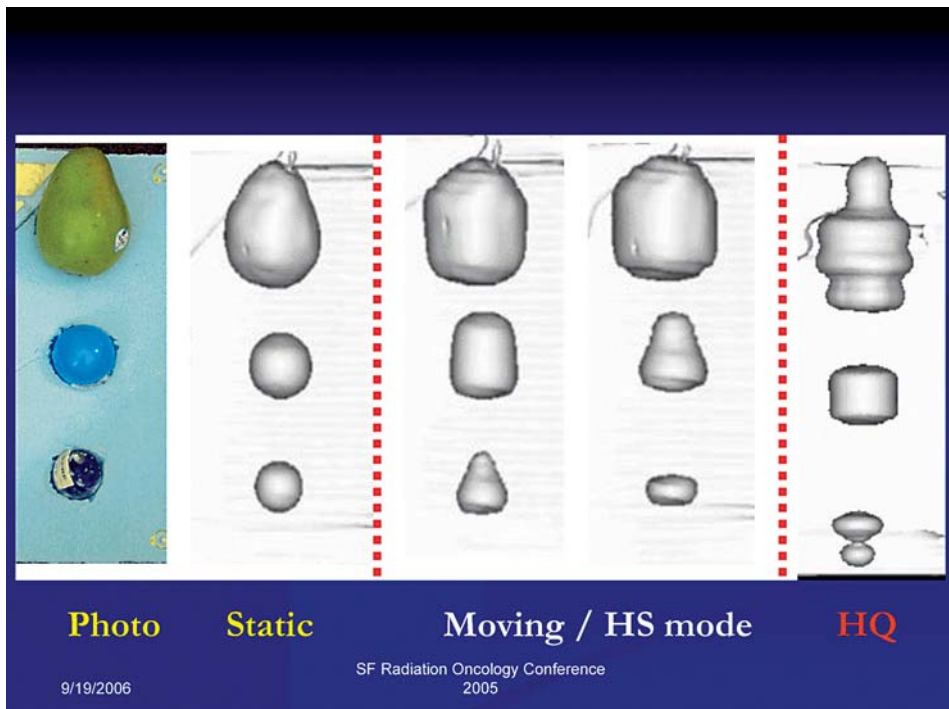


Fig. 1. Temporal aliasing resulting from helical scanning of moving objects. From left to right: photograph of static phantom objects, followed by surface rendering of objects after CT scan under static conditions. The next three columns of images show distortions when the object moves simulating respiration. The mid two columns of images are under conditions of high-speed mode; the rightmost column shows different artifacts when the object is scanned in the high-quality mode, where the pitch is one half that of the high-speed mode.

Artifacts in Imaging of Moving Objects

Artifacts due to motion during tomographic scans have been appreciated for many years [4, 5]. A common observation in scans of the thorax is the irregularity of beam's eye view of a target in the lung due to motion during scanning. Discontinuities in the diaphragm/lung interface are also commonly observed when scans are taken during light breathing. In 2002, one of the authors (J.H.K.) proposed an experiment to scan a phantom moving on a mechanical stage that simulated motion during respiration. He built a mechanical stage that sinusoidally oscillated along the longitudinal axis of the body with a periodicity of 4 s, and an amplitude of 1 cm; spherical objects (balls) placed in a block of Styrofoam rested on the stage. The left column in figure 1 shows a photograph of a portion of the phantom, where several rubber balls are visible. The second column is a surface rendering of these

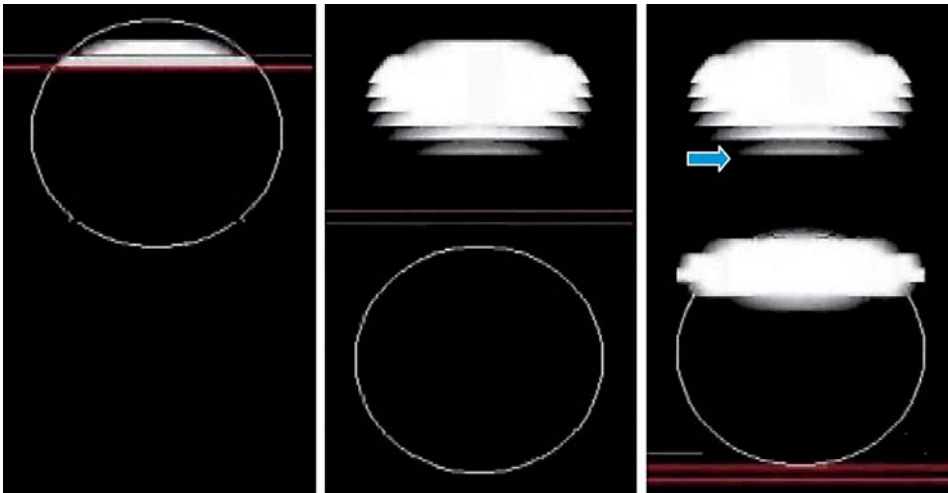


Fig. 2. Frames of a computer animation illustrating formation of images of a moving object. The white circle represents a sphere moving up/down sinusoidally. The white objects are CT slices formed during the intersection of the imaging plane with the spherical object. Note the lowest slice of the upper object (arrow) is actually the top of the sphere (see animation online at [WEB](#)).

objects when the phantom was scanned in the static mode. This surface rendering shows a geometrically accurate image of the objects. When the mechanical stage is set in motion and scans are acquired in the conventional helical mode, the resulting images of the spherical objects are significantly distorted as shown in the next three columns. The direction of the oscillatory motion is up/down along the columns. In one experiment, a 6-cm diameter ball was imaged during motion (2 cm peak to peak) as a distorted sphere with a longitudinal axis dimension of 4 cm, a full 2 cm smaller than its actual physical size. The technical term for this distortion is temporal aliasing.

A computer program was written to simulate the scanning process of moving objects, in order to improve our understanding of the effect [6]. Figure 2 is a composite image of the dynamic simulation. The sphere, which is represented by a thin white circle, is imaged in the simulation as two separate objects. The sphere moves over a much larger range than the objects imaged (see animation online at [WEB](#)). Notice the shape of the bottom slice of the upper object. This can be recognized as the top of the sphere by its curvature. The simulation graphically illustrates the presence of shuffling of the axial slices of the object. The asynchronous motions of organ/target and the monotonically advancing axial imaging of the object by the scanner can result in unusual perturbations in the imaging of a known object. Object parameters such as the size, shape, amplitude of motion, periodicity asyn-

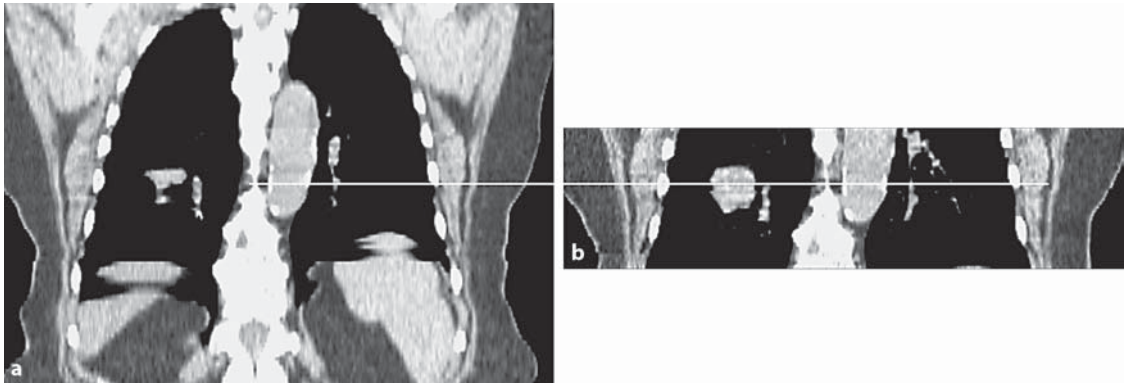


Fig. 3. **a** Coronal section through the patient scanned for lung tumor in the right lung. Section is through a light breathing CT scan. **b** One phase of a 4DCT scan through the same plane. Note the difference in tumor shape. Coverage longitudinally differs to spare the normal lung from dose, and focuses primarily on tumor motion.

chronously interact with scan parameters (slice thickness, pitch) through the respiratory phase at which the scanner intersects the moving object. Note in figure 1 that in the displayed coronal plane, it is possible for some objects to be lengthened while others are shortened. The effect depends on the specific phase of object motion as the scan plane intersects the sphere.

Temporal aliasing artifacts are also frequently observed in patient scans. Figure 3a is the coronal multiplanar reconstruction of a thorax scanned in the helical mode under the commonly applied condition of light breathing. One clearly sees the lung/diaphragm discontinuity artifacts. In comparison, figure 3b shows a comparable coronal section that has been reconstructed from a four-dimensional CT (4DCT) scan at a specific phase of the respiratory cycle. The difference in shape and size of the tumor between the two scanning techniques is apparent.

Four-Dimensional CT Scanning

Proof of the principle of respiration-correlated CT was shown by early investigators [7–9] in 2003, and 4DCT became commercially available in 2004. Respiration-correlated CT uses a surrogate signal, such as the abdominal surface, respiratory air flow, or internal anatomy to provide a signal that permits resorting of the reconstructed image data, resulting in multiple coherent spatiotemporal data sets at different respiratory phases. The scan time for 4DCT with multislice scanners is on the order of a few minutes, and postprocessing takes an additional 30 min if manual phase selection is required. The output of this process is typically 10 CT

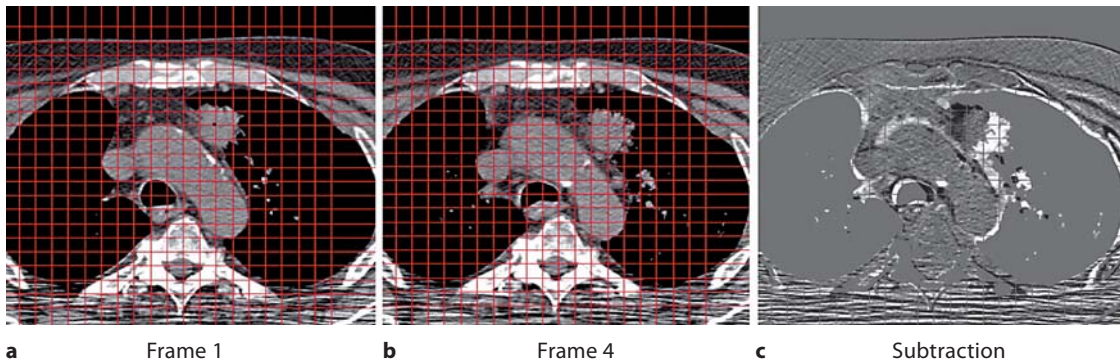


Fig. 4. Frames 1 (**a**) and 4 (**b**) are at the extrema of tumor motion. Subtracted (difference) image in **c** shows little bone motion, but significant motion of the tumor in the left-right axis (see animation of tumor motion online at [WEB](#)).

volumes, each with a temporal resolution of approx. 1/10 of the respiratory period. At Massachusetts General Hospital (MGH), we have used the GE/Varian 4D acquisition system, and have scanned about 150 patients to date. The 4DCT implementation relies on sensing the respiratory phase by using the Varian RPM system. Technical details of the approach are described elsewhere [10–12].

4DCT thus provides an imaging tool to quantify and characterize tumor and normal tissue shape and motion as a function of time. This provides the radiation oncologist and treatment planner with information essential in the design of an aperture that more adequately covers the internal target volume (assuming respiration during treatment is reproducible to that during CT simulation). 4DCT data can also be used as input in making treatment decisions on when to intervene with gating or other motion management strategies. In addition, the 4DCT data can be used as direct input into four-dimensional treatment planning, and to generate time-varying dose-volume histograms or isodose distributions [13, 14].

An effective method of conveying the utility of 4DCT is through computer animation. Typically, as used in the clinic at MGH, animations are played to display the position of tumor and normal anatomy over a respiratory cycle. In this print version, we display several static frames from the animation as well as difference images to show differences in anatomy as a function of time.

Figure 4 shows an interesting case provided by Dr. Noah Choi, thoracic radiation oncologist at MGH. As can be seen, the lesion is near the aortic arch. An animation shows tumor motion is primarily from left to right rather than cranio-caudal; the magnitude of the lateral motion is approximately ± 1 cm. Figure 4a, b shows the lesion in the extreme lateral positions; figure 4c shows the difference image. Regions of dark and light highlight areas of greatest motion. As can be seen,